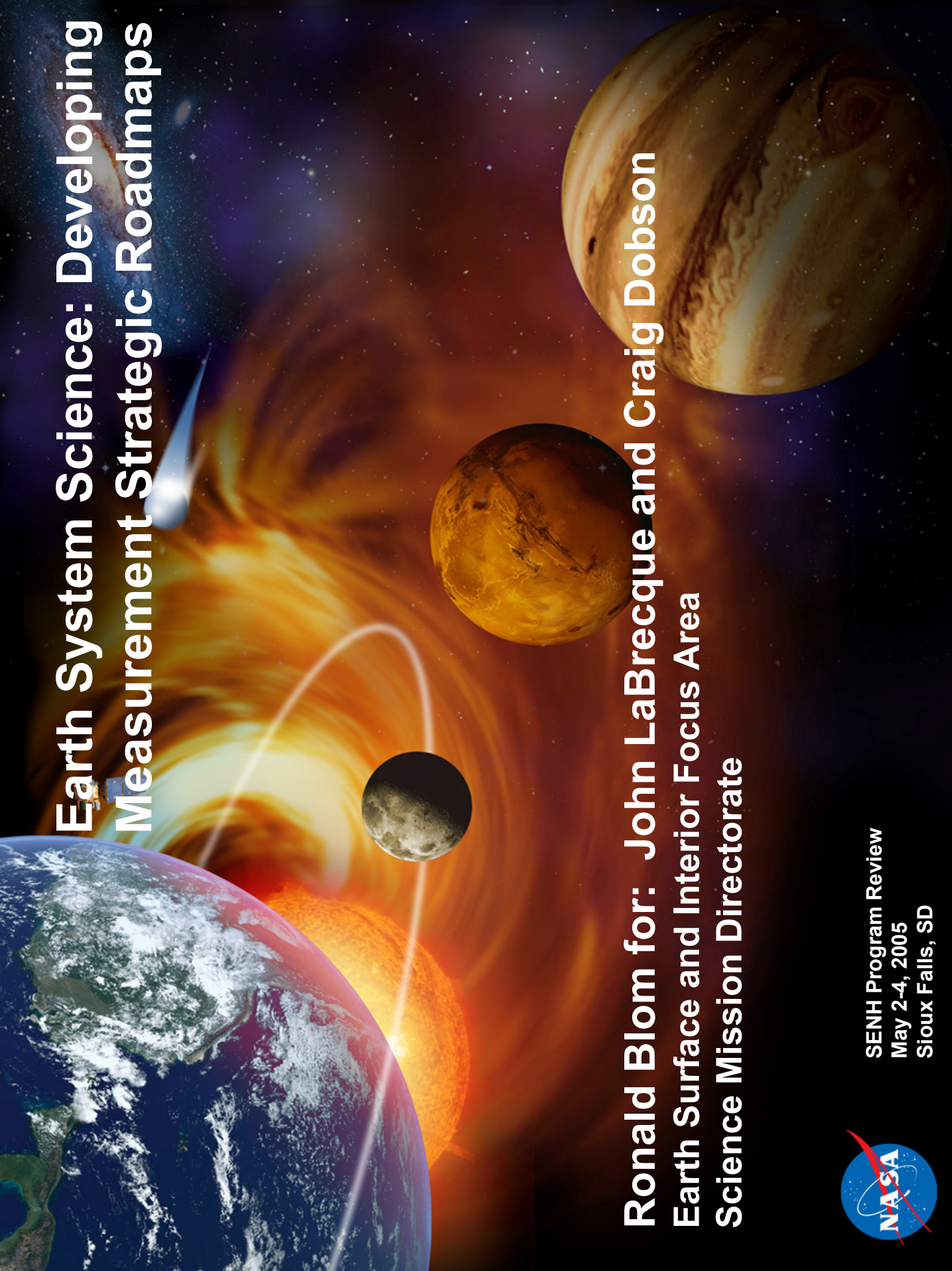




Earth System Science: Developing Measurement Strategic Roadmaps

Ronald Blom for: John LaBrecque and Craig Dobson
Earth Surface and Interior Focus Area
Science Mission Directorate



SENH Program Review
May 2-4, 2005
Sioux Falls, SD

Earth-Sun Division of the

Science Mission Directorate

Sun- Earth
Connection

Climate Variability
and Change

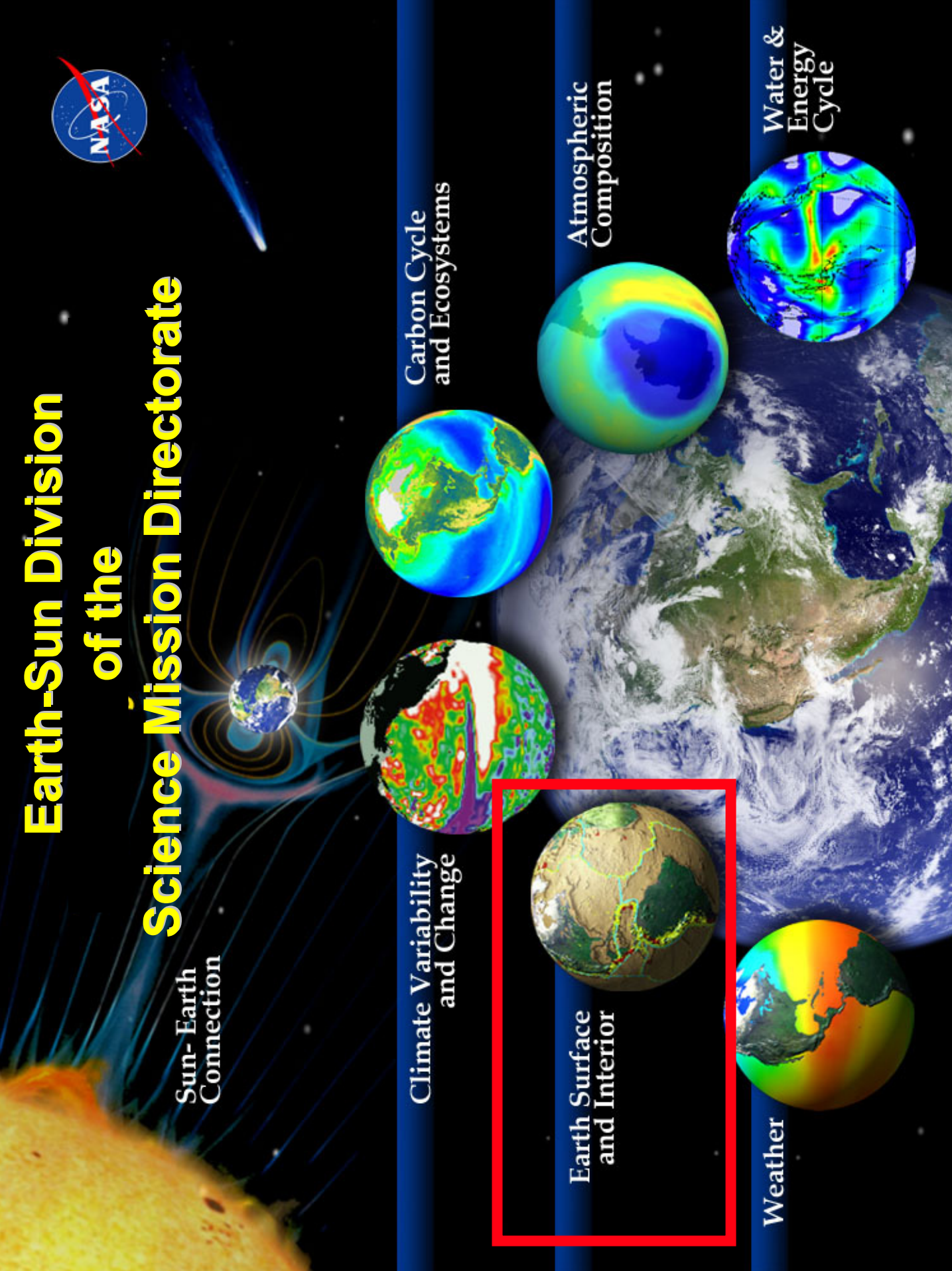
Carbon Cycle
and Ecosystems

Earth Surface
and Interior

Atmospheric
Composition

Weather

Water &
Energy
Cycle

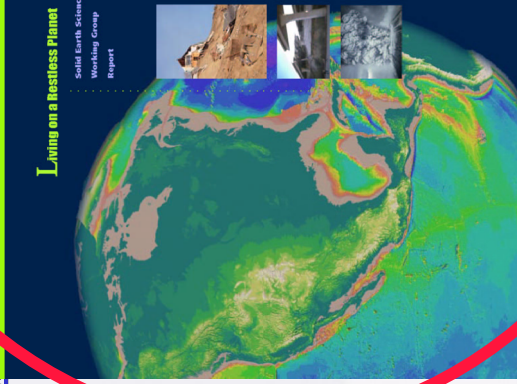


Earth Surface and Interior Focus Area

OMB Performance Measures: Enable 30 Day volcanic Eruption Forecasts with > 50% confidence by 2014

Enable estimation of earthquake likelihood in North American plate boundary with > 50% confidence by 2014

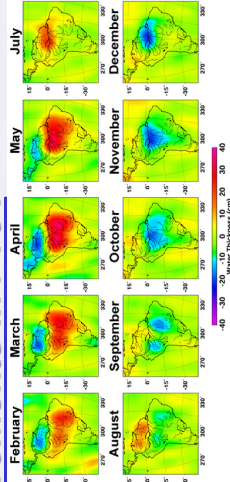
ESI Strategic Goals-



Living on a Restless Planet
Solid Earth Science Working Group Report

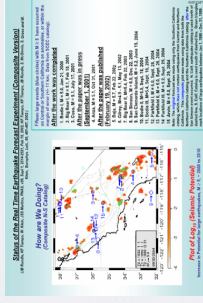
1. What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?
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5. What are the dynamics of the mantle and crust and how does the Earth's surface respond?
6. What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?

ESI Achievements in FY04



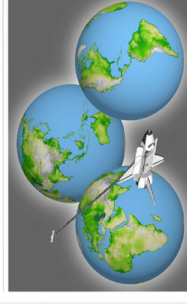
Earthquake Prediction

13 of 14 Earthquakes

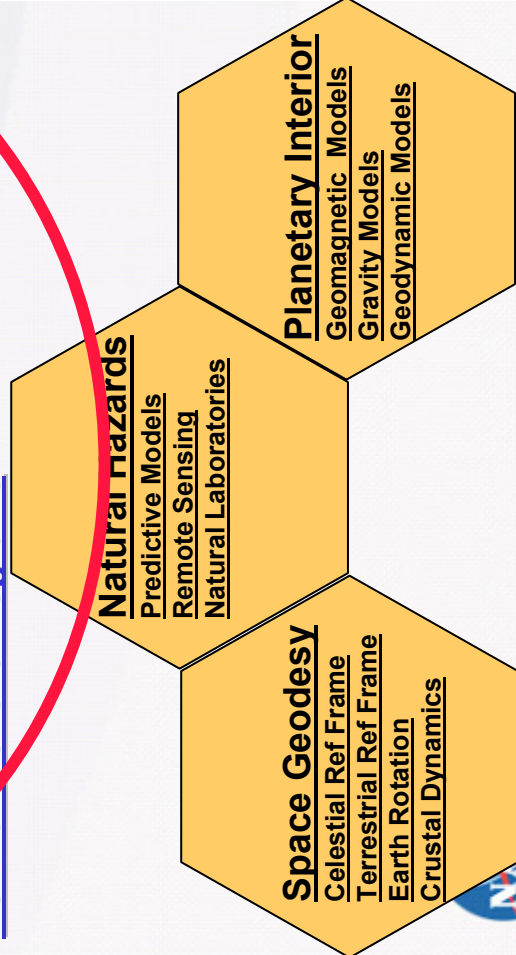


SRTM

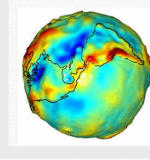
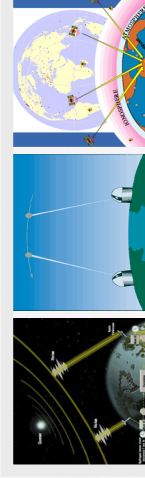
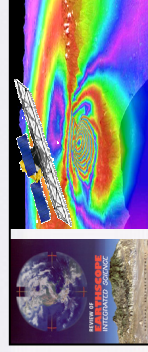
1st Uniform Global Topography



ESI Component Programs



ESI Strategic Priorities



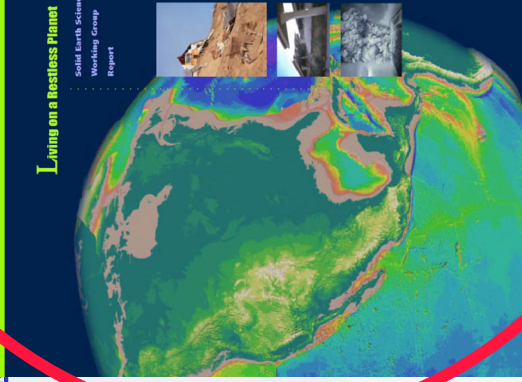
Earth Surface and Interior Focus Area

OMB Performance Measures: Enable 30 Day volcanic Eruption Forecasts with > 50% confidence by 2014

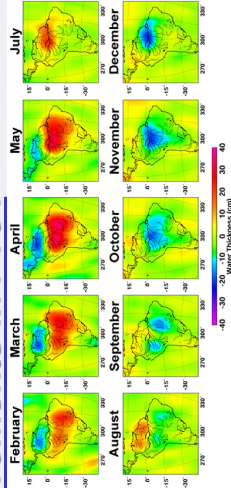
Enable estimation of earthquake likelihood in North American plate boundary with > 50% confidence by 2014

ESI Strategic Goals-

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ESI Achievements in FY04



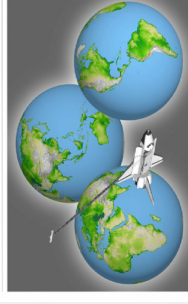
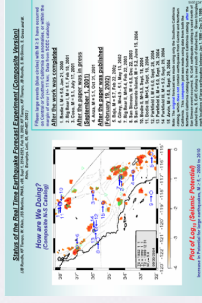
GRACE:1st
Time Variable
Gravity &
Mass Flux

Earthquake Prediction

13 of 14 Earthquakes

SRTM

1st Uniform Global Topography



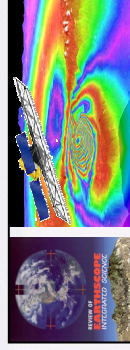
ESI Component Programs

Natural Hazards

Predictive Models

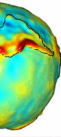
Space Ge
Celestial Ref
Terrestrial Re
Earth Rotation
Crustal Dyna

ESI Strategic Priorities



Develop Geodetic Imaging
Approach: Restless Planet

Available @
SolidEarth.jpl.nasa.gov

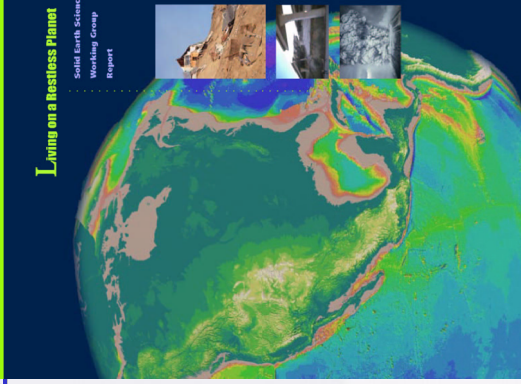


Partnerships (International, DoD, Focus Areas)

Earth Surface and Interior Focus Area

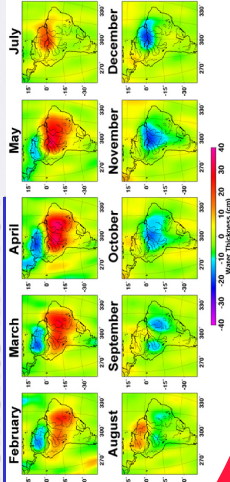
OMB Performance Measures: Enable 30 Day volcanic Eruption Forecasts with > 50% confidence by 2014
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ESI Strategic Goals-



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ESI Achievements in FY04



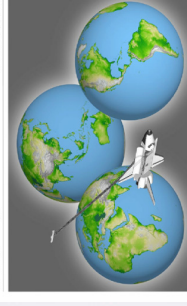
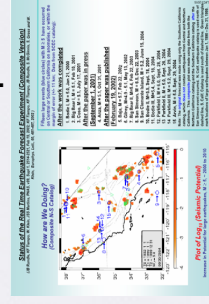
GRACE:1st
Time Variable
Gravity &
Mass Flux

Earthquake Prediction

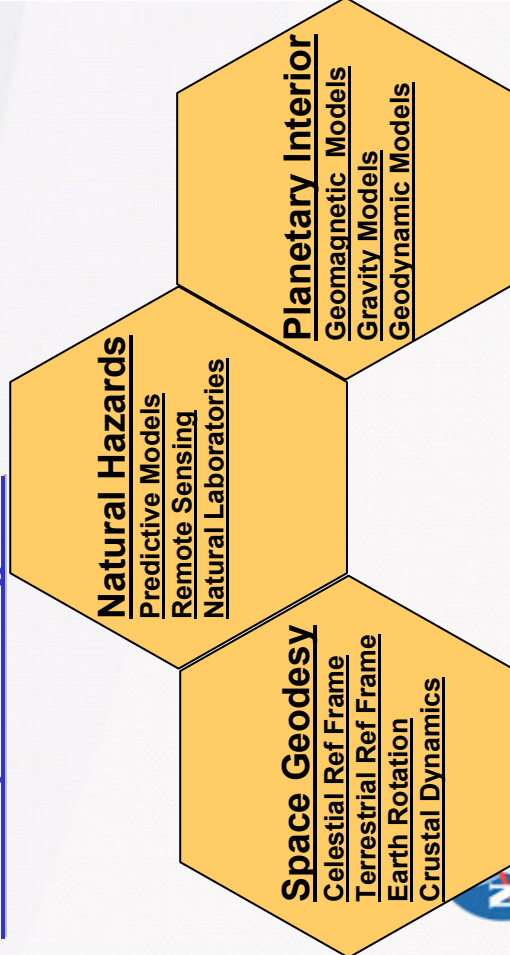
13 of 14 Earthquakes

SRTM

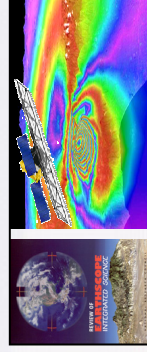
1st Uniform Global Topography



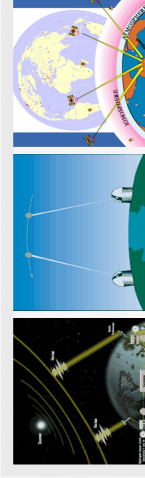
ESI Component Programs



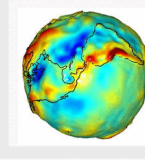
ESI Strategic Priorities



Develop Geodetic Imaging
 Approach: Restless Planet
 Initiative



Renew Global Geodetic
 Network
 Approach: Develop NGO:
 Work with Int'l Partners

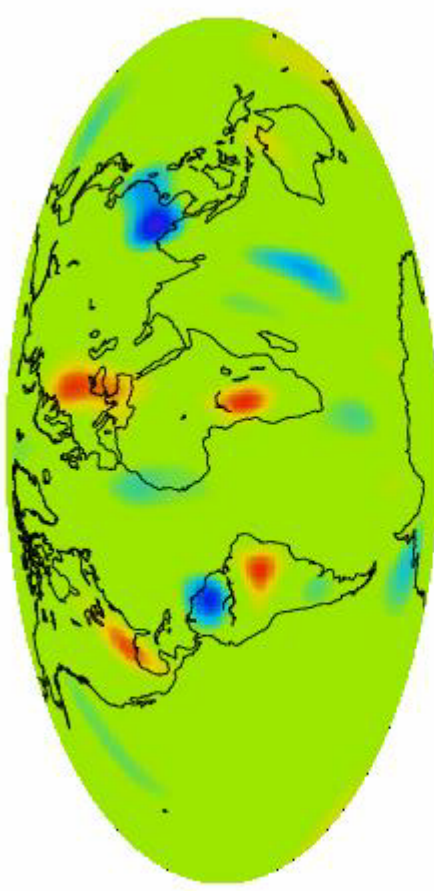


Expand Geopotential Field Exploration
 Approach: Technology Development &
 Partnerships (International, DoD, Focus Areas)

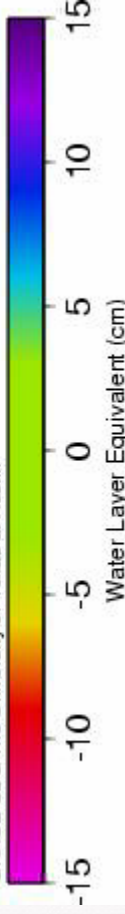
Monthly Water Mass Anomalies

The GRACE Mission

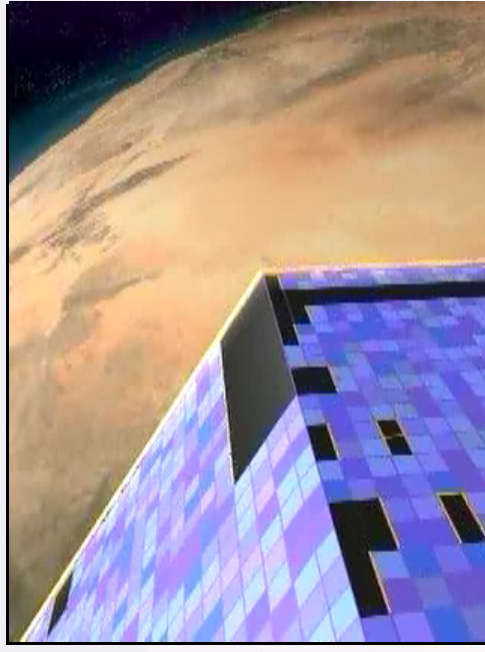
AUG-14-2002



GRACE SDS The University of Texas at Austin



[click graphic to view movie](#)



[click graphic to view movie](#)

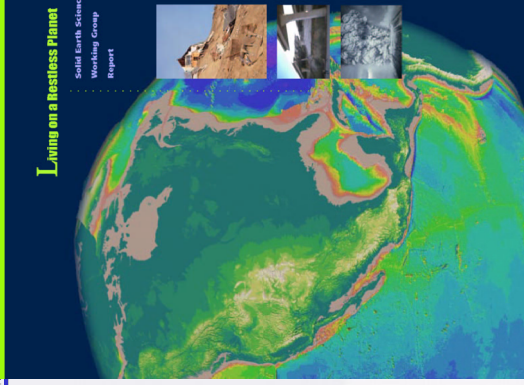


Earth Surface and Interior Focus Area

OMB Performance Measures: Enable 30 Day volcanic Eruption Forecasts with > 50% confidence by 2014

Enable estimation of earthquake likelihood in North American plate boundary with > 50% confidence by 2014

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ESI Component Programs

Natural Hazards

Predictive Models
Remote Sensing
Natural Laboratories

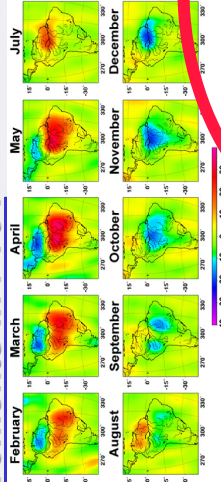
Space Geodesy

Celestial Ref Frame
Terrestrial Ref Frame
Earth Rotation
Crustal Dynamics

Planetary Interior

Geomagnetic Models
Gravity Models
Geodynamic Models

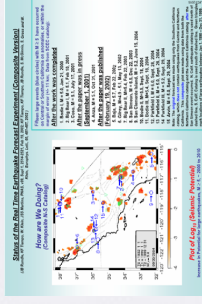
ESI Achievements in FY04



**GRACE:1st
Time Variable
Gravity &
Mass Flux**

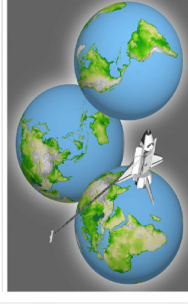
Earthquake Prediction

13 of 14 Earthquakes

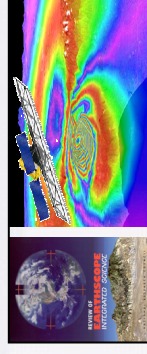


SRTM

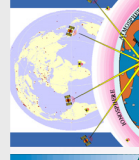
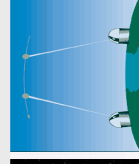
1st Uniform Global Topography



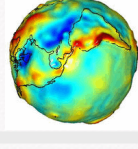
ESI Strategic Priorities



**Develop Geodetic Imaging
Approach: Restless Planet
Initiative**



**Renew Global Geodetic
Network
Approach: Develop NGO:
Work with Int'l Partners**



**Expand Geopotential Field Exploration
Approach: Technology Development &
Partnerships (International, DoD, Focus Areas)**

EarthScope Provided With 30 meter High Resolution SRTM Topography

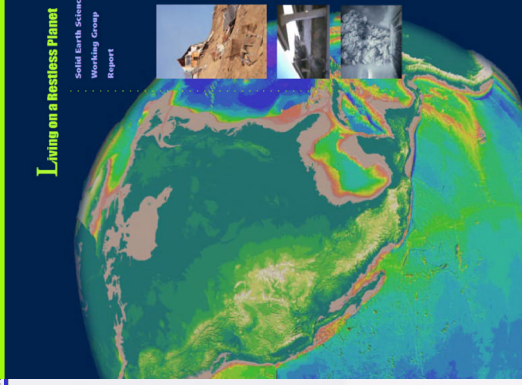


Earth Surface and Interior Focus Area

OMB Performance Measures: Enable 30 Day volcanic Eruption Forecasts with > 50% confidence by 2014

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ESI Component Programs

Natural Hazards

Predictive Models
Remote Sensing
Natural Laboratories

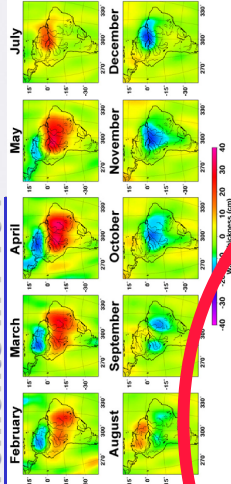
Space Geodesy

Celestial Ref Frame
Terrestrial Ref Frame
Earth Rotation
Crustal Dynamics

Planetary Interior

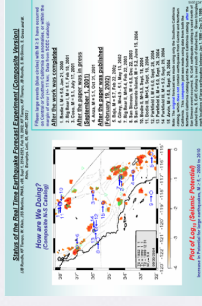
Geomagnetic Models
Gravity Models
Geodynamic Models

ESI Achievements in FY04



GRACE:1st Time Variable Gravity & Mass Flux

Earthquake Prediction 13 of 14 Earthquakes

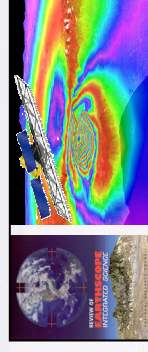


SRTM

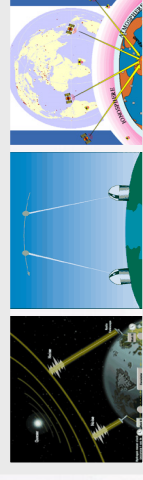
1st Uniform Global Topography



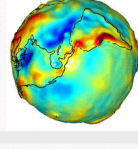
ESI Strategic Priorities



Develop Geodetic Imaging Approach: Restless Planet Initiative



Renew Global Geodetic Network Approach: Develop NGO: Work with Int'l Partners



Expand Geopotential Field Exploration Approach: Technology Development & Partnerships (International, DoD, Focus Areas)

13 of 14 Moderate sized Earthquakes Occurred in Identified High Risk Regions

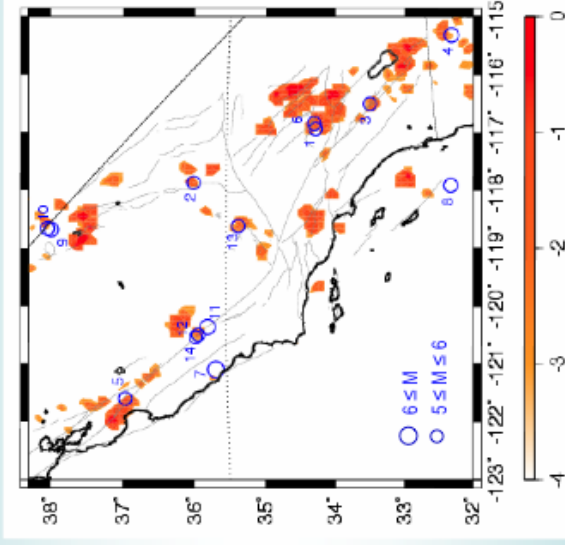
Study employed
statistical analysis to
identify high risk
regions.

NASA deploying
resources to study
these high risk
regions

Status of the Real Time Earthquake Forecast Experiment (Composite Version)

(JB Rundle et al., PNAS, v99, Supl 1, 2514-2521, Feb 19, 2002; KF Tiampo et al., Europhys. Lett., 60, 481-487, 2002; JB Rundle et al., Rev. Geophys. Space Phys., 41(4), DOI 10.1029/2003RG000135, 2003. <http://quakestim.jpl.nasa.gov>)

How are We Doing? (Composite N-S Catalog)



Plot of Log₁₀ (Seismic Potential)

Increase in Potential for large earthquakes, $M \geq 5$, ~ 2000 to 2010

Fourteen large events (blue circles) with $M \geq 5$ have occurred in Central or Southern California. Margin of error of the anomalies is ± 1.1 km; Data from S. CA. and N. CA. catalogs:

After the work was completed

1. Big Bear I, $M = 5.1$, Feb 10, 2001
2. Coso, $M = 5.1$, July 17, 2001

After the paper was in press (September 1, 2001.)

3. Anza, $M = 5.1$, Oct 31, 2001

After the paper was published (February 19, 2002.)

4. Baja, $M = 5.7$, Feb 22, 2002
5. Gilroy, $M = 4.9 - 5.1$, May 13, 2002
6. Big Bear II, $M = 5.4$, Feb 22, 2003
7. San Simeon, $M = 6.5$, Dec 22, 2003
8. San Clemente Island, $M = 5.2$, June 15, 2004
9. Bodie I, $M = 5.5$, Sept. 18, 2004
10. Bodie II, $M = 5.4$, Sept. 18, 2004
11. Parkfield I, $M = 6.0$, Sept. 28, 2004
12. Parkfield II, $M = 5.2$, Sept. 29, 2004
13. Arvin, $M = 5.0$, Sept. 29, 2004
14. Parkfield III, $M = 5.0$, Sept. 30, 2004

Note: The original forecast was made using both the full Southern California catalog plus the full Northern California catalog, but no corrections were applied for the different event statistics in the two catalogs. In this composite plot a correction was applied to account for the different event statistics in the two catalogs after the San Simeon event occurred. N. Calif. earthquake catalog is used north of dashed line, S. Calif. Catalog is used south of dashed line at latitude 35.5°. Green triangles mark locations of large earthquakes ($M \geq 5.0$) between Jan 1, 1990 – Dec 31, 1999.

CI #03-2015

Earth Surface and Interior Focus Area Roadmap

and volcanoes erupt?

What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?

How do tectonics and climate interact to shape the Earth's surface?

T

Knowledge Base

Advanced airborne, Repeat pass InSAR, High spatial & spectral visible & thermal imaging, high altitude Lidar altimeter

SRTM

High sensitivity Gravity & Geomagnetic Satellite Constellation

SAC-C
CHAMP.Oersted

**Global
Geodetic
Networks**

Next Generation Geodetic Network

T

global topography

International SAR Information Service

- Coordinated international global observation of land surface change for volcano, earthquake prediction, land use and ice cover, natural disaster management
- NASA mission leads in with instrument to target plate boundaries, coastal zones to measure surface deformation

High-Res topography to measure erosion, flooding, landslides, faults, & coal zones, etc.

Airborne remote sensing of surface change for long duration monitoring of earthquake, volcano, landslide, erosion, storm damage. Focus on geohazards natural laboratories e.g. Earthscope. Asia-Pacific Arc Natural Laboratory (A-PANL)

Ionospheric dynamics for geomagnetic modeling, atmospheric pressure for satellite gravity analysis, improved GPS orbits for geodesy

First uniform topography of land and ice surface, sparse hyperspectral visible & thermal imaging of land surface change

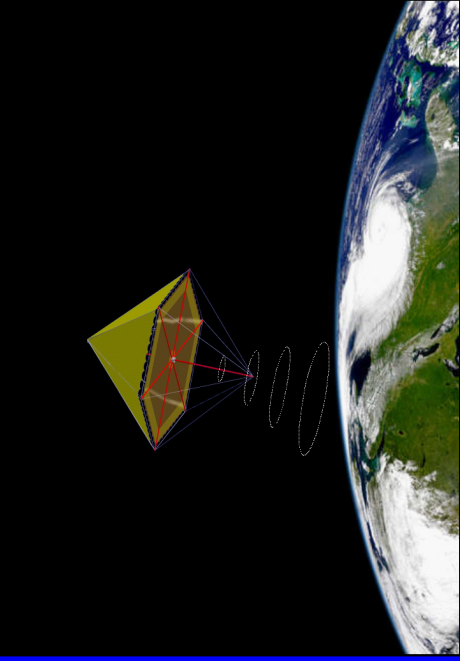
Gravity and geomagnetic models from this data provide estimates of water, atmospheric transport, plate boundary deformation, Earth interior forces, structure and deformation, geomagnetic field generation

Models & Prediction: mm accuracy of terrestrial reference frame, reliable and timely volcanic eruption & earthquake predictions, improved Earth system mass transport and geodynamic models, Earth interior models for glacial rebound and ocean loading.

2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
------	------	------	------	------	------	------	------	------	------	------	------

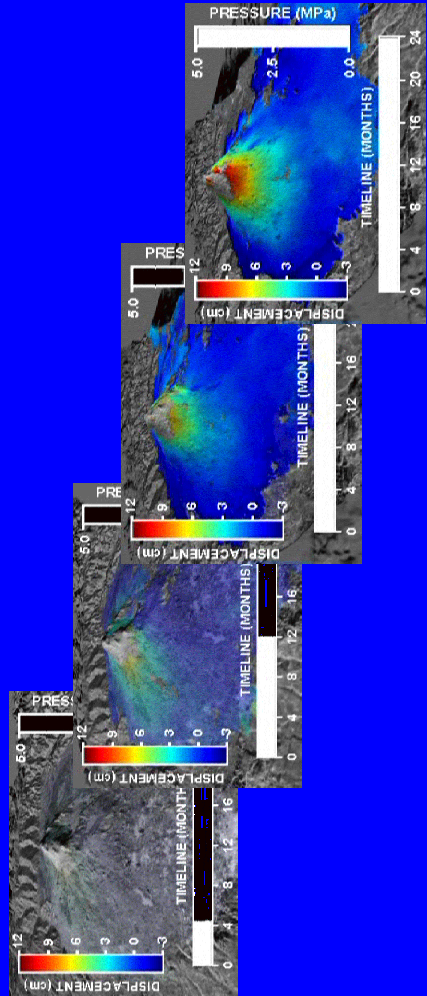
Restless Planet Initiative: Geodetic Imaging Development (over \$40M/yr)

Build the InSAR we need today

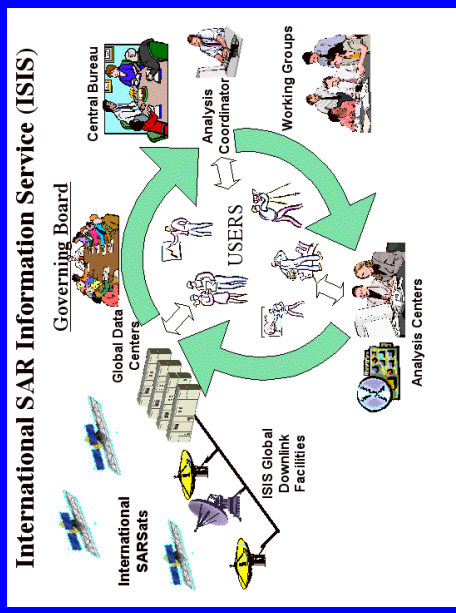


Develop the technology for tomorrow

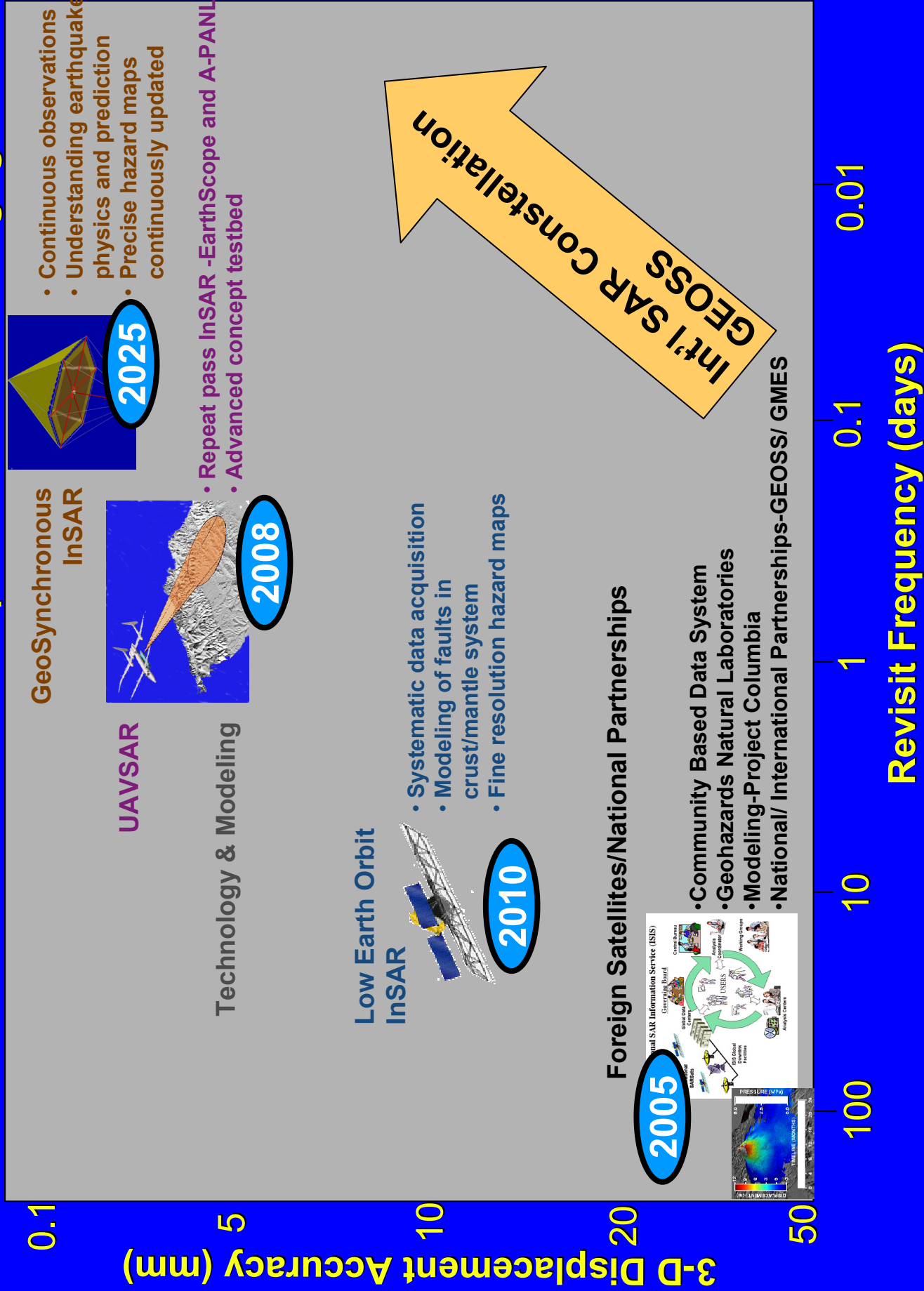
Accelerate development of data
handling and modeling capacity



Enable an international collaboration on
civilian SAR data and applications



Restless Planet Initiative: The Development of Geodetic Imaging: InSAR



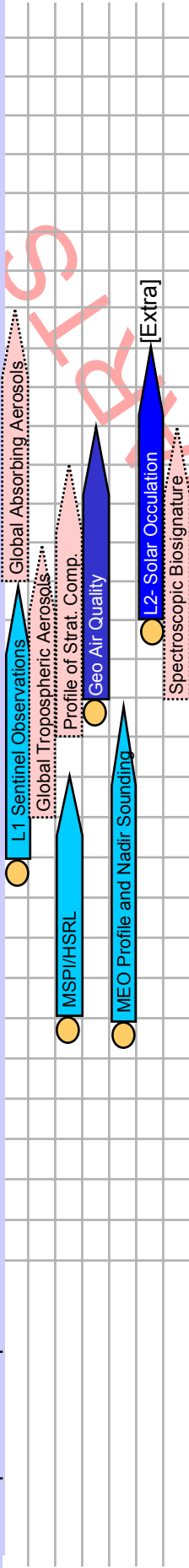
Earth Surface and Interior Measurements

Question	Objective (SESWG, NRC, EarthScope)	Investigations	Mission Target Date	Near-Term Measurements	Far-Term Measurements (2016 & Beyond
How do motions of the surface and interior of the Earth affect the global environment and life on Earth?	1. What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?	Surface Deformation	2010	Surface Topography/Deformation in 30 meter resolution- -Dual L-Band InSAR formation flight with Ionospheric imager -Next Generation Geodetic Network	-MEO/GEO 4-D InSAR Surface Deformation- continuous awareness
	2. How do tectonics and climate interact to shape the Earth's surface and create natural hazards?				
	3. What are the interactions among ice masses, oceans, and the solid Earth and their implications for sea level change?	High Resolution Topography	2014	Same as above	1 meter posting topography- -WS LiDAR
	4. How do magmatic systems evolve and under what conditions do volcanoes erupt?	Variability of the Earth's magnetic field	2015	SACC/SWARM COSMIC/CHAMP/ Oersted	-Geomagnetic Gradiometer Constellation
	5. What are the dynamics of the mantle and crust and how does the Earth's surface respond?	Variability of the Earth's Gravity Field	2011	GRACE FO Satellite Constellation to improve spatial and temporal sampling and reduce aliasing	Laser Interferometer Quantum Gravity Gradiometers
	6. What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?	Imaging spectroscopy of Earth's changing surface	2017	ASTER/ Imaging TIR	Continuous Full Spectrum 10 meter resolution VNIR/SWIR/TIR

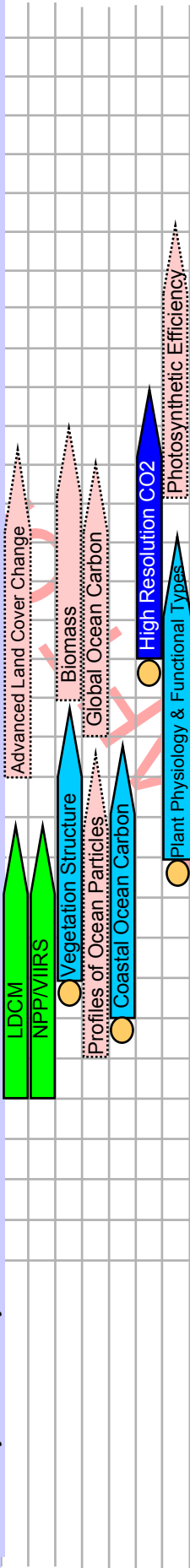
Earth System Science Measurements Roadmap

'05 '06 '07 '08 '09 '10 '11 '12 '13 '14 '15 '16 '17 '18 '19 '20 '21 '22 '23 '24 '25 '26 '27 '28 '29 '30 '31 '32 '33 '34 '35 '36

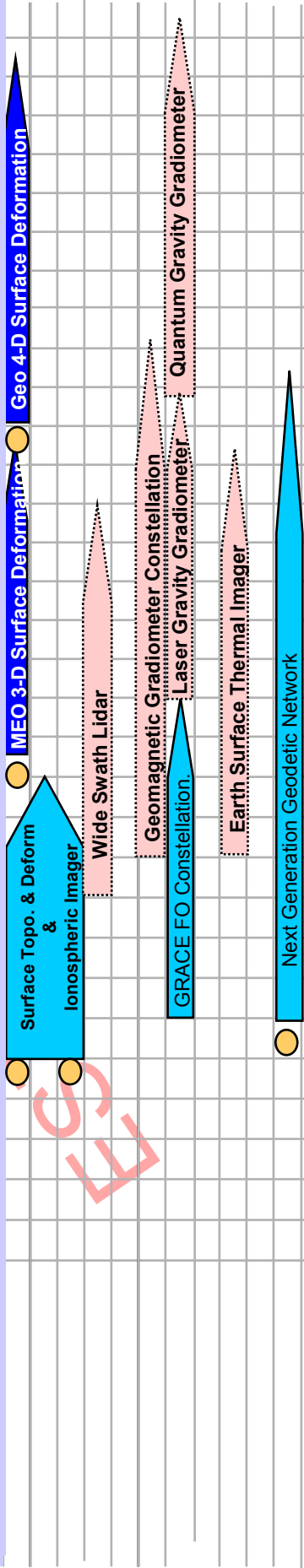
Atmospheric Composition:



Carbon Cycle & Ecosystems:

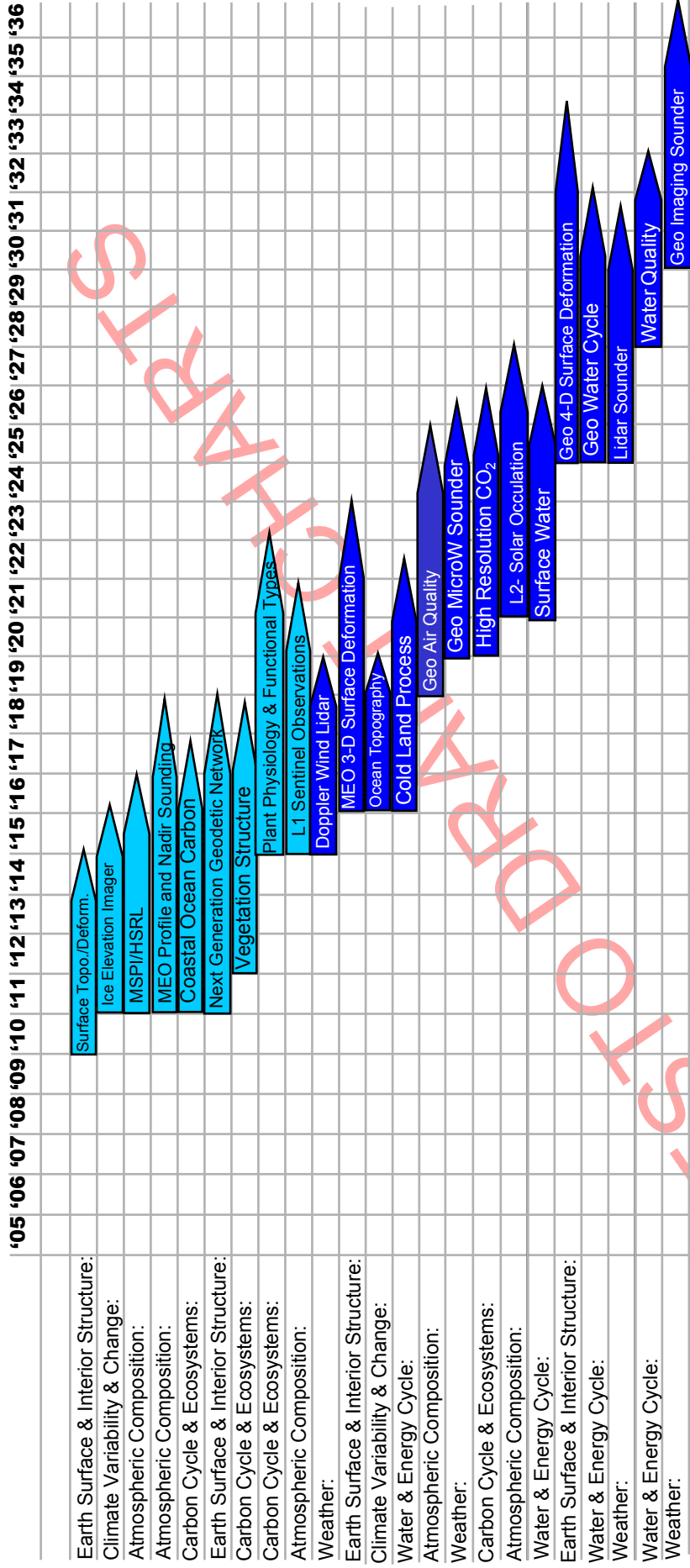


Earth Surface & Interior Structure:



- Near term defined missions
- Near Term Measurements not yet defined
- Far Term Measurements
- Non-prioritized Measurements
- Top priority measurements/missions

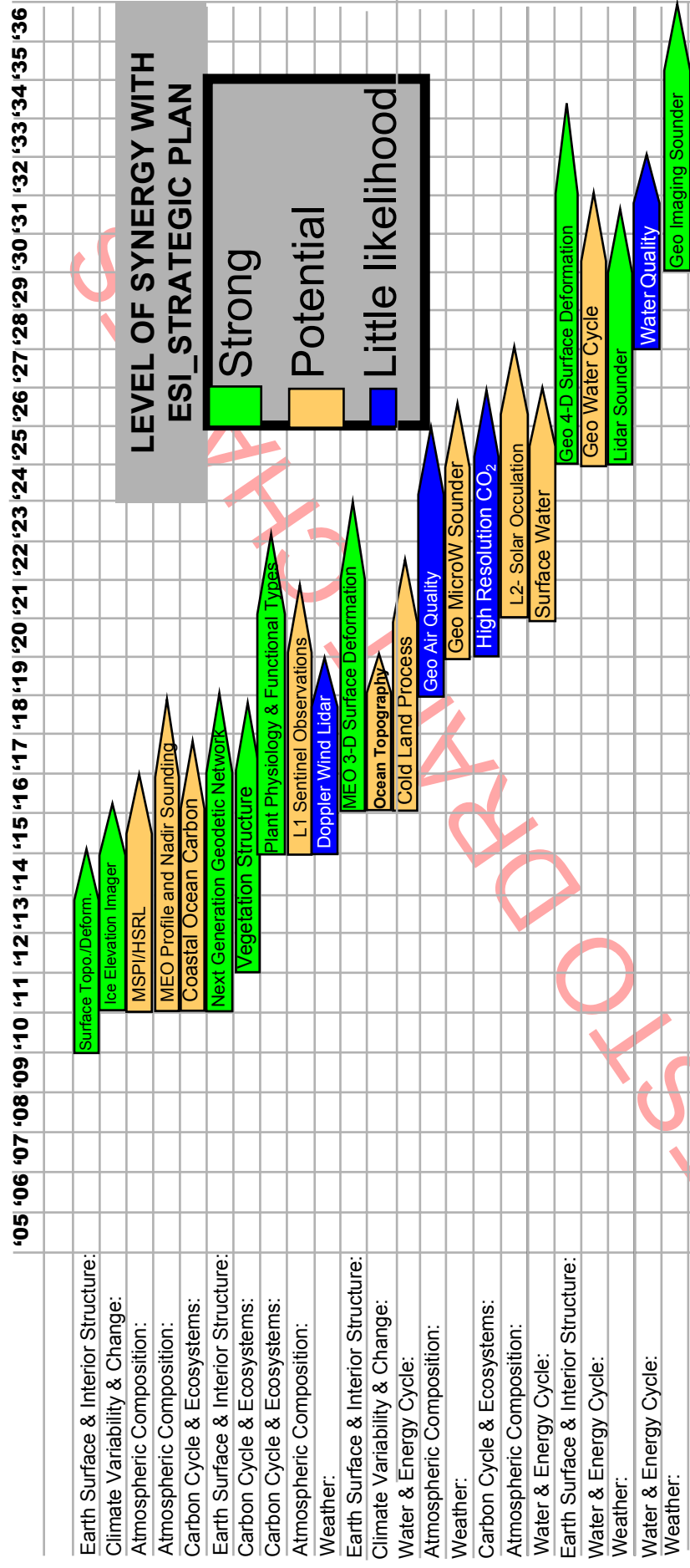
Earth System Science Priority Measurements Roadmap



Near Term Measurements not yet defined

Far Term Measurements

Earth System Science Priority Measurements Roadmap



Near Term Measurements not yet defined

Near Term Measurements

Earth Surface and Interior Focus Area

Mission Priorities

Plan	START NOW	START SOON	Requires CONSENSUS	Requires PARTNERSHIPS
Spiral 1 1-5 yrs	LEO InSAR Ionospheric Imager		GRACE Constellation	
Spiral 2 5-10 yrs	Wide Swath Lidar	Next Gen Geodetic Networks	Optically Interferometric Gravity Gradiometer Geomagnetic Gradiometer/ Ionospheric Sounder Constellations	MEO TIR Imager
Spiral 3 10-25 yrs	MEO/GEO InSAR	High LEO and Langrangian Pt. Beacons	Quantum Gradiometer	GEO VNIR-TIR Imaging Constellation

L-band LEO InSAR and Ionospheric Imager

Earth Surface & Interior/SEC

Electron Density Ionospheric Imager - (Spiral 1)

Science Objective

- Determine crustal structure and create predictive models for earthquake, volcanic eruption and landslide phenomena.
- Rated very high priority by EarthScope, NRC, SESWG, IGOS, and GEOSS.
- Determine structure and dynamics of the ionosphere to improve InSAR imaging of the Earth's surface as well as to better understand the ionospheric dynamics for Living with a Star/SSSC objectives. Ionospheric imager proof of concept mission instrument. Image flux tubes and current sheets and resolve ionospheric propagation errors to InSAR.
- *This mission addresses all six of the SESWG challenges (including dynamics of the magnetic field)*
- *This mission also addresses the SSSC2005 research focus H.2 --dynamics of the magnetosphere, ionosphere, and upper atmosphere...*

Mission Description

- Two or more spacecraft in polar Earth orbit
- L and/or P Band broadband (80 Mhz) quad polarization
- Antenna size of 45sq-m aperture area (ex., 15 m x 3 m) and antenna flatness of $\lambda/20$ or approximately 1 cm

Measurement Strategy

- Compatible with L-Band surface deformation measurement mission but includes modeling and measurement strategies to swath map the TEC and ionospheric electron density.
- Would employ split band processing and scanSAR to swath map ionospheric delay
- Would employ quad polarization to measure Faraday rotation.
- Needed for exploration of planetary surfaces and ionospheres

Technology Requirements

- Technology is ready for flight
- Ionospheric imaging largely constrained to specialized acquisition and processing approaches.



Wide Swath LIDAR

Earth Surface & Interior

Land and ice surface Topography and Topographic change (Spiral 2)

Science Objective

- Precisely measure land surface topography and topographic change, including where vegetated, and ice surface elevations with sub-decimeter vertical accuracy and 1-5 meter spatial resolution. LIDAR provides very high resolution topography and determines surface change in regions of low InSAR coherence (e.g. coastal zones, vegetated terrains, and river valleys).

Mission Description

- One spacecraft in low Earth orbit
- Wide-swath topographic height imaging LIDAR instrument
- Precision targeting to re-observe sites for change detection

Measurement Strategy

- Measure high-precision land surface and ice elevations to cm-levels using time-of-flight of a back scattered laser beam, separating vegetation cover and underlying ground
- Acquire an image of the height distribution of vegetation and the ground surface in a wide-swath with measurements that are contiguous along- and cross-track
- Differentiate surface types (land, vegetation, water, snow/ice) based on optical backscatter properties (intensity and depolarization at single or multiple wavelengths)
- The instrument consists of laser transmitters, a receiver telescope (≥ 1 m aperture, and receiver detectors and electronics for detection and timing of the laser backscattered echoes

Technology Requirements

- Long lifetime laser transmitters for space:
 - In space operating lifetime > 7 years
 - Linearly polarized, diffraction limited output beam
 - Wavelength compatible with high efficiency photon counting detectors
 - Optical linewidth (under modulation) < 3 pm
 - Modulation capable of cm accuracy ranging at > 1 KHz rates
 - Wall plug efficiency $> 15\%$
 - Average power > 20 W and sufficient for ≥ 8 simultaneous measurement swaths per transmitter
- ≥ 1 meter diameter telescope, image blur ≤ 1 arcsec
- Photon counting detectors
 - $> 50\%$ QE, < 1 KHz dark counts, max rate > 20 Mcps
 - Multi-year operating lifetime
- Photon timing histogram electronics with < 200 psec resolution
- Pointing knowledge better than 0.5 arcsecond to eliminate slant angle uncertainty height errors



L-Band MEO InSAR Constellation

Earth Surface & Interior

High Temporal Resolution 3-D Surface Deformation- (Spiral 2 or 3)		
Science Objective • Measure land surface topography and deformation with high temporal resolution using a constellation of synthetic aperture radars at MEO. Improved temporal resolution will provide better predictive capability and high resolution inversion of forces. • Rated priority #1 but only LEO InSAR is technically achievable in near term.	Technology Requirements • Lightweight deployable radar antenna and structure (ex, deployable membrane, L-band, 10m x 40m area) • Large aperture electronically scanning arrays -low mass (<2-4kg/sq-m structure + aperture + electronics) • low power (<4KW DC), rad-hard (>2Mrad) low profile integrated T/R modules with high efficiency (>60%), low loss (<1dB) and high power (>10W) switches and phase shifters, packaging/attachment technologies on flex, radiation shielding (>10Mrad) • High-speed digital RF electronics (synthetic beam antenna, digital beamforming with 30 phase-center channels and true time delay capability), metrology (for aperture flatness)/calibration, thermal management. • Pointing knowledge of approx. 0.01deg and control of approx. 0.05deg, free-flying satellite of 3000-15,000km elevation, repeat track to better than 100-200m accuracy. • On-board storage and down-link (2-10GB, 1GB/s), real-time GNSS sub meter level positioning • High efficiency (>25%) power generation (solar cells+battery) integrated with antenna	
	Mission Description • Constellation of spacecraft in medium Earth orbit • L Band quad polarization with 80 Mhz bandwidth • Antenna size 400 sq-m aperture area with antenna flatness of lambda/20. • Right-left pointing by electronic beam steering +/- 40deg (at lowest orbit elevations). • 2mm/yr 3-D displacement rate accuracy, 1-2 day repeat with 12 revisit time.	
	Measurement Strategy • Measure land surface topography from MEO altitude. The MEO option provides improved temporal coverage and accessibility relative to LEO orbit. Simultaneous measurement will provide high resolution 3-D deformation maps. • Differential repeat-pass InSAR techniques are used for surface deformation measurements. • Quad polarization with broadband signal will be used to resolve ionospheric structure and delay.	

GEO InSAR Constellation

Earth Surface & Interior

4-D Globally Synoptic Surface Deformation - (Spiral 3)

Science Objective

- Measure land surface topography and deformation with high temporal resolution using a constellation of synthetic aperture radars in geosynchronous orbit. This scenario option provides near continuous temporal coverage and accessibility.
- Only LEO InSAR is technically achievable in near term.

Mission Description

- Constellation of spacecraft in inclined geosynchronous orbit
- L- Band quad polarization broadband >80 Mhz signal structure
- Antenna size >700 sq-m aperture area (ex, 30m diameter circular antenna) with antenna flatness of $\lambda/20$. Electronic beam steering (elev & azimuth) of $\pm 8^\circ$ (required).
- 1-2mm/yr 3-D displacement rate accuracy, 12-hour repeat and near continuous temporal coverage and accessibility (0-12 hour revisit) relative to LEO.

Measurement Strategy

- Measure land surface topography from LEO altitude. Interferometry for vector deformation measurement with global coverage.
- Differential repeat-pass InSAR techniques are used for surface deformation measurements.
- Quad polarization broadband will be used to resolve ionospheric structure and delay.

Technology Requirements

- Spot beams - lightweight deployable radar antenna and structure (ex, deployable membrane)
- L-band, 30m diameter circular -large aperture electronically scanning arrays -low mass (<1-2kg/sq-m structure + aperture + electronics)
- Low power (<30KW DC), rad-hard (>2Mrad) low profile integrated T/R modules with high efficiency (>60%), low loss (<1dB) and high power (>5W) switches and phase shifters, packaging/attachment technologies on flex, radiation shielding (>10Mrad)
- High-speed digital RF electronics (synthetic beam antenna, digital beamforming with 30 phase-center channels and true time delay capability), metrology (for aperture flatness)/calibration, thermal management, embedded passives and electronics.
- Pointing knowledge of approx. 0.003deg and control of approx. 0.2deg, free-flying satellite of 35,789km elevation, repeat track to better than 100-200m accuracy
- On-board storage and down-link (2-10GB, 1GB/s), real-time GNSS sub meter level positioning
- High efficiency (>25%) power generation (solar cells+battery) integrated with antenna.



Earth Surface and Interior Focus Area

Mission Priorities

Plan	START NOW	START SOON	Requires CONSENSUS	Requires PARTNERSHIPS
Spiral 1 1-5 yrs	LEO InSAR Ionospheric Imager		GRACE Constellation	
Spiral 2 5-10 yrs	Wide Swath Lidar	Next Gen Geodetic Networks	Optically Interferometric Gravity Gradiometer Geomagnetic Gradiometer/ Ionospheric Sounder Constellations	MEO TIR Imager
Spiral 3 10-25 yrs	MEO/GEO InSAR	High LEO and Langrangian Pt. Beacons	Quantum Gradiometer	GEO VNIR-TIR Imaging Constellation

Next Generation Geodetic Network

Earth Surface & Interior

Land Surface Deformation, Mass Flux and Precision Earth and Planetary Navigation (Spiral 2)	
Science Objective • Measure Earth orientation, satellite and space probe precision navigation and maintain celestial and terrestrial reference frames. For advanced Earth System measurements including surface deformation, mass flux associated with sea level change, dynamics of the Earth's planetary interior, lunar and planetary exploration. • Rated high priority because current capability has significantly deteriorated albeit need for new positioning and timing capability in Earth missions, GNSS and spectrum changes, and need for lunar and planetary exploration.	Technology Requirements • Advanced GNSS receiver • <5-cm real-time kinematic positioning in all spatial dimensions, with a 1-cm goal. • Reconfigurable GNSS receiver to allow measurement of GPS III signals as well as the Russian GLONASS GNSS and/or European Galileo GNSS. • Receiver/antenna with ability to track dual frequency carrier phase down to 5 degree elevation with <1-cm multi-path error. • Laser reflectors and antenna calibration of GPS, Galileo and GLONASS satellites • Automated SLR ground station • X,S,K band VLBI small aperture broad band (>2 GHz RF band width or 4 Gbs sampling rate) • Uniformly distributed network of 20 broadband linked collocated SLR, GNSS, VLBI fiducial stations • Continuous relative positioning at 1 mm resolution or better between fiducial site sensors • High LEO/Low MEO orbiting geodetic satellites capable of both transceiver type GNSS rebroadcast and SLR positioning with laser reflectors. These would duplicate the functions of the current LAGEOS type satellites in acting as Geodetic monuments in space but would also serve as GNSS antennas in space to calibrate all three GNSS systems (GPS, GALILEO and GLONASS) as well as to cross calibrate the SLR and GNSS reference frames. • Lagrangian geodetic monuments with optical and RF (GNSS compatible) broadcasts. • GNSS satellites with calibrated antenna phase centers and laser retroreflectors.
Mission Description • A new generation of geodetic ground network using collocated SLR, GNSS, VLBI instruments • Space based geodetic satellites at MEO and Lagrangian points at L1, L2, L4, L5- next generation LAGEOS type for both GNSS and SLR operations	
Measurement Strategy • Renewal of the current aging geodetic networks with high accuracy real time integrated network of GNSS, VLBI, and SLR networks. • Provide sub-centimeter orbits for spacecraft including GNSS satellites. • Lagrangian point geodetic optical and RF beacons to provide inner solar system precision navigation.	



Earth Surface and Interior Focus Area

Mission Priorities

Plan	START NOW	START SOON	Requires CONSENSUS	Requires PARTNERSHIPS
Spiral 1 1-5 yrs	LEO InSAR Ionospheric Imager		GRACE Constellation	
Spiral 2 5-10 yrs	Wide Swath Lidar	Next Gen Geodetic Networks	Optically Interferometric Gravity Gradiometer Geomagnetic Gradiometer/ Ionospheric Sounder Constellations	MEO TIR Imager
Spiral 3 10-25 yrs	MEO/GEO InSAR	High LEO and Langrangian Pt. Beacons	Quantum Gradiometer	GEO VNIR-TIR Imaging Constellation



GRACE Constellation Gravity Gradiometer

Earth Surface & Interior

Earth Gravity Field Variability (Spiral 1)

Science Objective

- To measure gravity field changes due to changing ocean circulation and warming, hydrologic and cryospheric mass flux, crustal deformation, and Earth core dynamics and mean gravity field for orbits. Gravity field variability is a direct measure of mass, when combined with altimetry, gravity provides a measure of ocean density change associated with heating or crustal uplift due to ice load melting.
- A constellation of gravity sensors is most likely a requirement for any time variable gravity measurement beyond GRACE in order to overcome the noise induced by incomplete measurement of the oceanic and atmospheric dynamics. These enhanced measurements of ocean and atmospheric dynamics will also advance the modeling of oceanic and atmospheric weather.
- *This mission addresses 4 of the six SESWG challenges (including dynamics of the magnetic field)- SESWG report p.60*
- *This mission also addresses the SSSC2005 research focuses H.1,H.2 and H.3 and the development of exploration technology through the measurement of aeronomy and mass flux in the atmosphere.*

Mission Description

- Two or more GRACE satellite pairs in low Earth polar orbit
- Observe the geoid to 300-500 km resolution each month with mm geoid error.

Measurement Strategy

- Measure changes in the distance between two spacecraft in low-Earth orbit separated by ~200 kilometers to detect perturbations caused by the Earth's gravity field, using accelerometers to separate out the non-gravitational accelerations.
- Extend the current GRACE technology with a constellation approach using multiple satellite pairs.
- Constellation of satellites needed to improve spatio-temporal sampling and to reduce measurement aliasing due to atmospheric and oceanic dynamics.

Technology Requirements

- None beyond current GRACE instrumentation
- Lower cost of sensors will be important in the constellation approach



Optically Interferometric Gravity Gradiometer

Earth Surface & Interior

Earth Gravity Field Variability (Spiral 2)

Science Objective

- Measure geopotential reference surface and Earth gravity field. To measure gravity field changes due to ocean circulation changes, hydrologic and cryospheric mass flux, crustal deformation, and Earth core dynamics. Gravity field variability is a direct measure of mass, when combined with altimetry, gravity provides a measure of ocean density change associated with heating or crustal uplift due to ice load melting.
- The combination of cm level swath mapping altimetry and 50 km spatial resolution in the gravity field will provide the ability to measure variability in boundary current flows critical to fisheries, weather and climate.
- This 50-100 km resolution window will also view major tectonic features such as subduction zones, rift valleys and mountain belts currently only poorly imaged in the satellite gravity field.
- *This mission addresses 4 of the six SESWG challenges (including dynamics of the magnetic field)- SESWG report p.60*
- *This mission also addresses the SSSC2005 research focuses H.1,H.2 and H.3 ad the development of exploration technology through the measurement of aeronomy and mass flux in the atmosphere and oceans.*
- GRACE and GOCE missions being studied for measurement strategies

Mission Description

- Two or more pairs of spacecraft in low Earth polar orbit
- Observe the geoid to 50 km each month with sub-cm geoid error.

Measurement Strategy

- Measure changes in the distance between two spacecraft in low-Earth orbit separated by 50-200 kilometers to detect perturbations caused by the Earth's gravity field, along with a force reduction system on each spacecraft to reduce non-gravitational forces.
- Laser inter satellite ranging provides one thousand times higher ranging resolution than GRACE.
- Lower altitude improves sensitivity to higher degrees
- Constellation of satellites needed to improve spatio-temporal sampling and to reduce measurement aliasing due to atmospheric and oceanic dynamics.

Technology Requirements

- Single-mode laser with power 10-30 mW, natural frequency noise <100 MHz over 100 second sampling time
- Laser frequency stabilization system with stability of 1.E-15 rms over 100 seconds; Laser frequency measurement system with accuracy <10⁻⁵(-5)Hz rms for averaging times of 100 seconds, over dynamic range of ~5 MHz
- Gravitational Reference Sensor with a test mass isolated to less than 1.E-15 m/s² rms over 100 seconds and a measurement system for providing a measure of the spacecraft position with respect to the test mass with accuracy of 1 nanometer rms over 100 seconds
- Micro-Thruster system to adjust the spacecraft position to stay centered on the test mass to within 1 nanometer rms over 100 seconds, with thruster requirement of 2-100 micro-Newton with step size 0.1 micro-Newton and noise less than 0.01 micro-Newton rms over 100 seconds.)
- Ultra high accuracy MEMS accelerometers
- Field emission electric propulsion
- Micro-Newton or pulsed plasmas thrusters



Geomagnetic Gradiometer Constellation

Earth Surface & Interior

Earth Geodynamo and Surface Dynamics (Spiral 2)		
Science Objective • Provide 10 picotesla measurement accuracy of the Earth's internal geomagnetic field. Objective is to measure temporal changes in the crustal/mantle and oceanic electric current flow to determine electrical conductivity changes due to structure and dynamics and improve resolution of the crustal, mantle and core mean fields to resolve structure and dynamics. • Rated third priority because of existing and planned satellite missions up to 2012 (SWARM, CHAMP, Oersted, SAC-C, COSMIC) • <i>This mission supports the SESWG Challenge of understanding geomagnetic field variability!</i> • <i>This mission supports SSSC2005 H.2 and H.3 through measurements of ionospheric currents and magnetospheric magnetic fields, ionospheric electron density, and atmospheric pressure fields.</i>	Technology Requirements • High accuracy zero drift vector magnetometer (laser pumped vector helium) • Light weight GNSS phased array antenna of 1 sq meter or larger • Advanced real GNSS (GPS III Galileo, GLONASS, DORIS) remote sensing receiver capable of phased array operation. • Tethered satellite operations	
Mission Description • 12 nanosatellites with picotesla accuracy tethered vector magnetometers polar orbiting magnetometers with large radial displacement (> 5 Km) for individual gradient measurement. • Each satellite equipped with GNSS remote sensing instruments (limb and reflection sounding).		
Measurement Strategy • Measure the geomagnetic gradient tensor (for Curl B) to resolve magnetospheric current flux and • Measure ionospheric electron density through GNSS tomography. • Knowledge of ionospheric electron density and current flow will allow separation of sources and distinction of internal and external magnetic sources. • Constellation will provide high temporal and spatial resolution of geomagnetic gradients • GNSS remote sensing would also provide atmospheric surface pressure valuable to weather modeling and gravity field interpretation as well as ocean surface deflection for tsunami detection.		



Quantum Gravity Gradiometer

Earth Surface & Interior

Earth Gravity Field and Gravity Field Variability (Spiral 3)

Science Objective

- Measure geopotential reference surface and Earth gravity field. To measure mean gravity field to very high accuracy and resolution and gravity field changes due to ocean circulation, hydrologic and cryospheric mass flux, crustal deformation, and Earth core dynamics. Gravity field variability is a direct measure of mass, when combined with altimetry, gravity provides a measure of ocean density change associated with heating or crustal uplift due to ice load melting.
- The combination of cm level swath mapping altimetry and 50 km spatial resolution in the gravity field will provide the ability to measure variability in boundary current flows critical to fisheries, weather and climate. This 50-100 km resolution window will also view major tectonic features such as subduction zones, rift valleys and mountain belts currently only poorly imaged in the satellite gravity field.
- ESA GOCE gravity gradiometer mission is in development and being studied as a prototype for the much more sensitive Quantum Gravity Gradiometer.

Mission Description

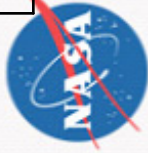
- Two or more spacecraft in low Earth polar orbit
- Observe the geoid to 100 km resolution (50 km goal) each month with with sub-cm geoid error.

Measurement Strategy

- Measure gravity gradient tensor using Bose-Einstein condensate as test mass
- Will provide sensitivity to cross track density variations
- Constellation of satellites needed to improve spatio-temporal sampling and to reduce measurement aliasing due to atmospheric and oceanic dynamics.
- Best for exploration of fine crustal structure
- Best for exploration of planetary interiors due to minimal requirements on positioning

Technology Requirements

- Compact cold atom beam source as proof mass.
- Calibrated zero drift proof mass positioning for five or more elements of gradient tensor.
- Micro-Thruster system to adjust the spacecraft position to stay centered on the test mass to within 1 nanometer rms over 100 seconds, with thruster requirement of 2-100 micro-Newton with step size 0.1 micro-Newton and noise less than 0.01 micro-Newton rms over 100 seconds.)
- Precision attitude determination system with sub-micro-arc second accuracy to minimize rotation contamination of measurement



Earth Surface and Interior Focus Area

Mission Priorities

Plan	START NOW	START SOON	Requires CONSENSUS	Requires PARTNERSHIPS
Spiral 1 1-5 yrs	LEO InSAR Ionospheric Imager		GRACE Constellation	
Spiral 2 5-10 yrs	Wide Swath Lidar	Next Gen Geodetic Networks	Optically Interferometric Gravity Gradiometer Geomagnetic Gradiometer/ Ionospheric Sounder Constellations	MEO TIR Imager
Spiral 3 10-25 yrs	MEO/GEO InSAR	High LEO and Langrangian Pt. Beacons	Quantum Gradiometer	GEO VNIR-TIR Imaging Constellation

Earth Surface Thermal Imager

Earth Surface & Interior

High Resolution Imaging of Tectonic Thermal Sources (Spiral 2)		
Science Objective •Determine changes in the temperature of the Earth's surface due to tectonic activity including volcanic sources and surface deformation. •Map surface lithology/chemistry and structure. •Many applications and algorithms in advanced development	Technology Requirements •Miniaturized high SNR TIR optical systems. •Low mass, deployable optics. •Multi-wavelength 2D TIR arrays cooled and uncooled. •Low power, low mass coolers.	
Mission Description • 10-30 meter spatial resolution high SNR TIR imager with low latency broadcast. Selected VNIR-SWIR bands desirable. •Multi spectral imaging in 0.4-2.5, 3-5 and 7-14 micron range •Hyperspectral TIR desirable for use on UAV. •LEO/MEO polar orbit		
Measurement Strategy •Extend current ASTER capability with higher resolution, better SNR, and low latency, and more frequent observation. ASTER has already exceeded its operational lifetime. ETM+ severely limited due to single thermal band and scan line corrector problem. No planned replacement for ASTER. Landsat Data Continuity Mission (LDCM) does not include thermal. •Data would provide low latency warning of tectonically induced thermal signatures such as volcanic eruptions and wild fires •High spatial resolution would provide significant enhancement of lithological mapping along tectonic features such as faults.		



NASA Strategic Planning

Two chances to be heard

1. NASA Strategic Roadmap

http://www.nasa.gov/about/strategic_roadmaps.html

Roadmap #9: Earth Science and Applications from Space: Research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems.

Co-Chairs: Charles Kennel- USCD-Scripps

Diane Evans- JPL

Panel Member: Sean Solomon- Carnegie Institution

2. NRC Decadal Study for Earth Science

RFI-closing: May 15th

(Space Studies Board)

http://www.nannospace.org/new_page_95.htm

To generate prioritized recommendations from the Earth and environmental science and applications community

Co-Chairs: Rick Anthes Berrien Moore

Sub-Panel: Solid-Earth Hazards, Resources, and Dynamics

Chair Solid Earth: Brad Hager-MIT

Exec Committee: Mary Lou Zoback

